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Philip E. Neumann for the degree of Master of Science in Water Resources Science presented on November 8, 2012

Title: Shallow Aquifer Storage and Recovery (SASR): Regional Management of Underground Water Storage in Hydraulically Connected Aquifer-stream Systems.

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Roy D. Haggerty

A novel mode of shallow aquifer management could increase the volumetric potential and distribution of underground, freshwater storage: Shallow aquifer storage and recovery (SASR). In this mode, water is efficiently stored in basin fill aquifers with strong hydraulic connection to surface water. Regional numerical modeling can provide a linkage between storage efficiency and local hydrogeologic parameters, which in turn may contribute to useful rules guiding how and where water can be stored. This study: (1) uses a calibrated model of the central Willamette Basin (CWB), Oregon to correlate SASR storage efficiency to basic hydrogeologic parameters using the stream depletion factor (SDF); (2) uses SDF to identify regions of high storage efficiency, and (3) estimates potential volumetric storage and injection rates for storage-efficient regions. Potential storage for the CWB is estimated to be 2.40 million m^3. Given areal average hydrogeologic parameters, 8 wells—roughly 35 m deep and 0.3 m diameter—would be capable of managing this storage on an annual basis. Given otherwise similar conditions, greater depth to groundwater would yield greater volumetric potential, greater injection rates, and either unchanged or increased efficiency.

Shallow Aquifer Storage and Recovery (SASR): Regional Management of Underground Water Storage in Hydraulically Connected Aquifer-stream Systems

by
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APPROVED:

Major Professor, representing Water Resources Science

Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Philip E. Neumann, Author

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDICIES

LIST OF APPENDIX FIGURES

Shallow Aquifer Storage and Recovery (SASR): Regional Management of Underground Water Storage in Hydraulically Connected Aquifer-stream Systems

CHAPTER 1
INTRODUCTION

Background

In times of increasing freshwater demand and reduced certainty of supply, the value of additional storage is high. Aquifer storage and recovery (ASR) is an accepted tool for freshwater storage in the United States as well as internationally (Pyne, 2005), and this trend is exemplified in the state of Oregon (Woody, 2009). By injecting seasonal surplus water into suitable aquifers via well, water can be effectively stored for use at a later time. Though desired temporal offset between injection and pumping varies by application, injected water is typically pumped from the aquifer during the following dry season as water resources become increasingly scarce. In locations where ASR is suitable, solely pumping from an aquifer leads to long-term depletion of surface water resources (Bredehoeft, 2011a). ASR allows for seasonal pumping of the aquifer without long-term consequence to surface water.

Maliva & Missimer (2008) remind us that the benefits of any ASR strategy are not gained from injection alone, but from maintenance of injected water as increased storage within an aquifer. If this increased storage is not maintained, the “recovery” component of ASR is ultimately at the volumetric expense of surface water within the aquifer-stream system. In the western United States—where water use is governed by the prior appropriation doctrine—volumetric reduction to surface water can result in injury to senior surface water rights (i.e., irrigation, instream flow, and municipal supply). For ASR to be of value to society within the framework of western water law, it must therefore be targeted at locations that maximize the maintenance of increased storage over a desired timeframe.

Recovery efficiency is a commonly used ASR metric, but is used to quantify changes in water quality between injection and recovery phases of an ASR cycle. Recovery efficiency can provide valuable insight on advective and diffusive factors that govern the quality of recovered water, but it does not inherently address the regional maintenance of storage. It can be defined as

$$E_{recovery} = \frac{Volume\ of\ injected\ water\ recovered}{Volume\ of\ injected\ water} \times 100 \tag{1}$$

Storage efficiency is suggested by the author as an additional metric with greater utility for regional water resource managers, and is presented in this study as

$$E_{storage} = \frac{Volume\ of\ stored\ water}{Volume\ of\ injected\ water} \times 100 \tag{2}$$

where the numerator and denominator are both considered over a given time period, t. The distinction between *storage* and *recovery* efficiency is discussed further in Appendix A.

Storage efficiency can vary greatly depending on aquifer characteristics. It is likely to be greater and more certain in deep, confined aquifers with high degrees of geologic isolation from surface water—smaller and less certain in shallow, unconfined or partially confined aquifers. The global convention has consequently been to target ASR in confined, geologically isolated aquifers. Though recharge of shallow aquifers is not a new concept, its utility for seasonal storage is constrained by uncertainty. Detailed hydrogeologic characterization is required to estimate maintenance of storage through time. In lieu of uncertainty, shallow aquifer recharge operations are well suited to the recharge of water without direct recovery, often with the goals of aquifer and streamflow restoration (Schilfgaarde, 2007).

There may still be reason to further explore shallow aquifers as an additional venue for ASR. Confined, geologically isolated aquifers are a prime resource for the current mode of ASR, but are of limited volumetric storage potential and geographic extent. Many cities and agricultural regions do not have access to such aquifers, and efficient storage in such aquifers will reach an upper volumetric limit. Less ideal, shallow aquifers—unconfined or partially confined—may offer additional storage over a wider geographic extent.

Despite current uncertainty of storage efficiency in most shallow aquifers, there is no intrinsic barrier to storage-efficient ASR. Forthright regional hydrogeologic characterization could increase the certainty of storage efficiency in shallow aquifers, and a robust framework could restrict ASR development to highly efficient locations. The use of shallow aquifers for the efficient storage of freshwater will be referred to as shallow aquifer storage and recovery (SASR).

It should be emphasized that this study does not address all factors that would lead to successful implementation of SASR. The primary concern of this study is hydrogeologic feasibility and a Willamette Basin case study (Appendix B) provided preliminary results to this end. Future studies may wish to consider the wide range of additional technical, sociopolitical, and economic constraints of SASR. Such studies may also investigate potential for secondary functions of SASR such as the treatment of wastewater, which has been shown proven effective using ASR (Page, 2010). Citizens and state water resource managers can ultimately decide if, when, and how SASR can help reach water resource management goals.

Storage with SASR

In confined aquifers, a high degree of geologic isolation from surface water helps ensure high storage efficiency. A confined aquifer will respond to injection, to an extent, by local expansion of the pore or fracture matrix and compression of water. In an ideally confined aquifer with no connection to surface water, these local changes would propagate outward to the surrounding aquifer, the average head in the aquifer would increase, and these changes would not propagate to a surface water boundary. If an equal amount of water is pumped from the confined aquifer, the inverse process would occur and the aquifer would ideally return to its original state. Storage efficiency in this situation would be 100%.

Due to unconfined or partially confined conditions common to shallow aquifers, there is no geologic safeguard against lost storage. Nevertheless, Bredehoeft and Kendy (2008) demonstrate that efficient, shallow aquifer storage is feasible given the appropriate balance of aquifer-stream characteristics. They use the stream depletion factor (SDF), first introduced by Jenkins (1968), as a way to quantify the surface water effects of pumping and recharge in a shallow, basin fill aquifer (South Platte River, Colorado). Their work adds to a suite of publications by Bredehoeft, all of which chronicle the surface water complexities of groundwater pumping and recharge in similar systems (Bredehoeft, 2002; Bredehoeft & Durbin, 2009; Bredehoeft, 2011a; Bredehoeft, 2011b). Though the significance of this work can be applied to any form of recharge (i.e., natural infiltration, irrigation returns, and surface spreading), it is applied in this study to the characteristic ASR practice of injection via well.

When attempting to quantify and compare processes in the natural world, it is often useful to consider variable groups that together form a characteristic time or length scale. This approach was taken by Jenkins (1968) in defining the stream depletion factor (SDF) which defines the timescale over which head perturbations will propagate through an aquifer. In an ideal, homogeneous aquifer of infinite extent and thickness,

$$SDF = \frac{a^2 S}{T} \tag{3}$$

where a [L] is the distance between a well and stream, S [-] is the storage coefficient of the aquifer material, and T [L^2T^{-1}] is the transmissivity of the aquifer material. SDF [T] is typically calculated in days. When applied to the Jenkins variant of the Glover and Balmer (1954) solution, the resulting equation proves a convenient approach to estimate changes to streamflow caused by pumping or injection:

$$\frac{q}{Q} = \mathrm{erfc}\left(\frac{\mathrm{SDF}}{4t}\right)^{\frac{1}{2}} \tag{4}$$

where $q[L^3T^{-1}]$ is the change in rate of streamflow due to pumping, Q $[L^3T^{-1}]$ is the rate of pumping or injection, and t [T] is the duration of continuous pumping or injection.

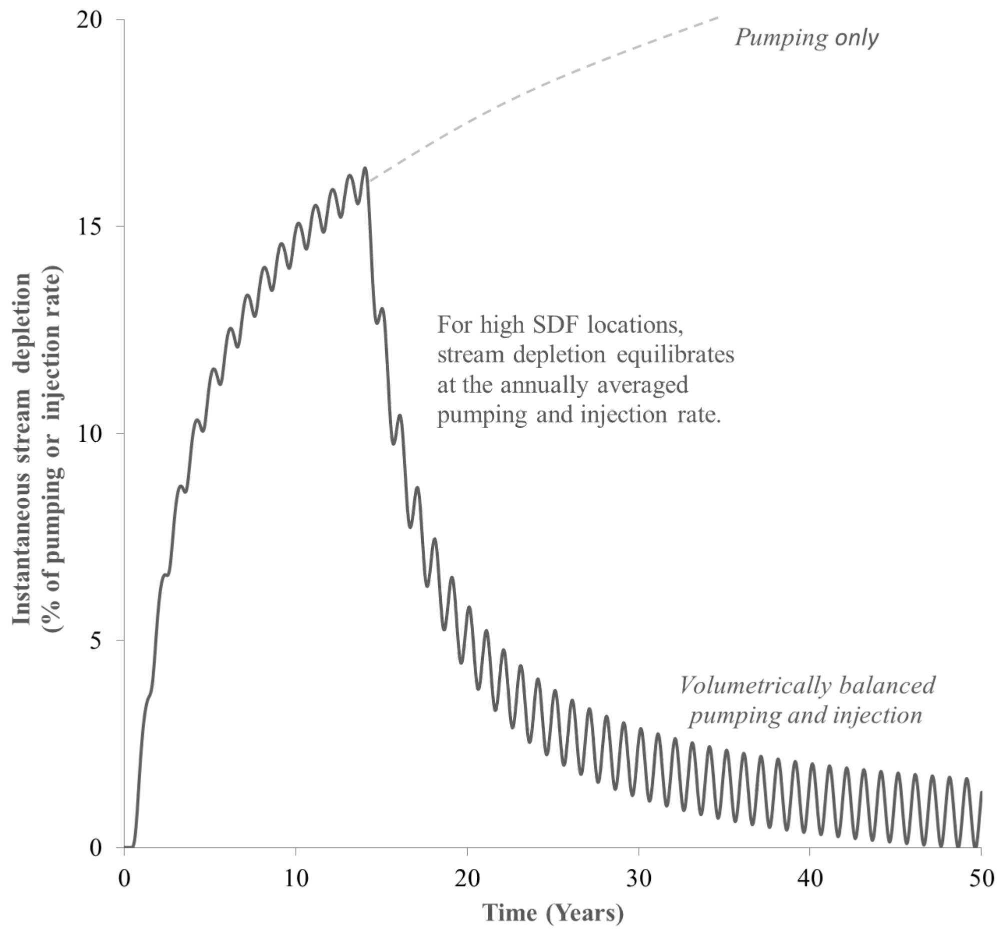

Figure 1-1: Modeled effects on streamflow from seasonal pumping and injection at a high SDF location. Initial summer pumping (June, July, August) from this location will equilibrate at a long-term average stream depletion that is 25% the instantaneous summer rate. When summer pumping is volumetrically balanced by winter or spring injection, there is a long-term net-zero effect on streamflow. Seasonal effects are negligible where SDF is sufficiently high.

Using a numerical model approach to the Glover and Balmer (1954) solution, Bredehoeft and Kendy (2008) demonstrate that while volumetric balance of pumping and injection provides a long term, net-zero effect on streamflow, significant seasonal change in streamflow can occur. These effects are realized as either streamflow depletion or what the author refers to as streamflow accretion. The former is a result of pumping and the latter a result of injection. Bredehoeft and Kendy (2008) most importantly demonstrate that increased SDF serves to dampen seasonal effects on streamflow (Figure 1-1). Increased SDF acts as a low pass filter for seasonal variation.

Where pumping and recharge are volumetrically balanced and SDF is sufficiently high, the change to streamflow is negligible throughout the year—significantly less than 5% in the case of Figure 1-1. A cross sectional perspective can be useful in interpreting how this storage process can occur in a hydraulically connected aquifer-stream system (Figure 1-2). The exchange of water between aquifer and surface water relies on the propagation of head change to a surface water boundary. If the ultimate head change at the boundary is minimal, so is the change in exchange between groundwater and surface water. Storage is in this case efficient.

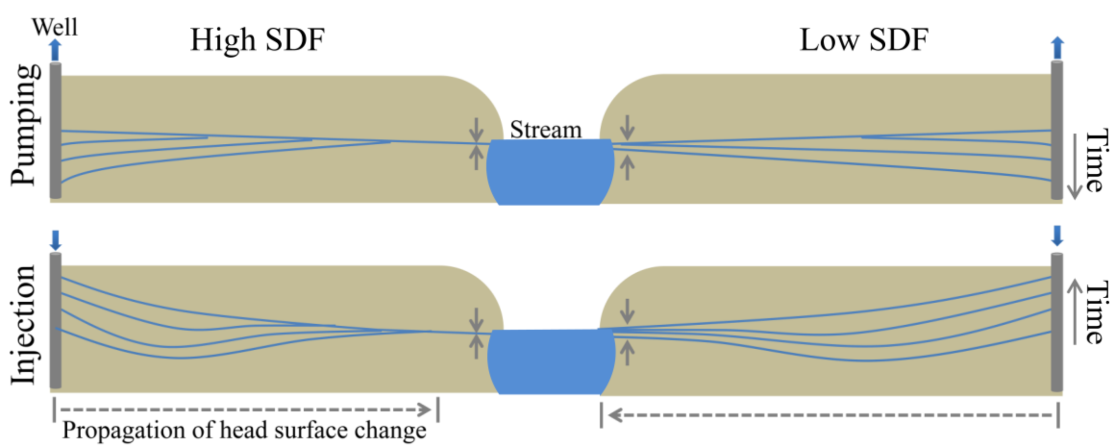

Figure 1-2. Comparison of high and low SDF wells. Each well employs seasonal pumping and injection in two homogeneous, unconfined, shallow aquifers, with different values of storage coefficient and transmissivity. Blue lines depict the changing head surface over time. The well in a high SDF location completes a pumping-injection cycle with minimal head change propagation reaching the stream. The result is minimal change to streamflow, which indicates efficient storage with SASR. For the well in a low SDF location, substantial head change propagates to the stream before completion of a pumping-injection cycle. Significant changes to streamflow result, suggesting SASR is not feasible at this particular well.

Objectives

Implementation of SASR will first require that storage is technically feasible given regional aquifer conditions. Secondly, it will require a robust framework by which technically feasible locations can be identified and managed. The primary objectives in this study are summarized with the following questions: (1) How prevalent are the high-SDF locations described by Bredehoeft & Kendy (2008) in a complex, basin wide setting? (2) If such locations exist, will additional hydrogeologic constraints allow for sufficient volumetric storage potential at acceptable injection rates? (3) In the interest of regional water resource management, is there a mechanism by which potential storage sites could be effectively identified and managed?

CHAPTER 2
Methods

The Model

This study uses a calibrated model of the central Willamette Basin (CWB), Oregon to simulate injection at numerous wells screened for shallow, basin fill aquifers. The framework for this model is the modular, three-dimensional, finite-difference, groundwater flow model (MODFLOW) developed by the U.S. Geological Survey (USGS). The model itself is based on the USGS, transient MODFLOW model of the CWB (M. Gannett and T. Conlon, personal communication, January 9, 2012). Areal resolution for the CWB model is 305 m and local grid refinement is not used. At the time of publication, the CWB model has not yet been approved and any results included in this study are therefore provisional.

The model is calibrated over a 2-year period that spans water years 1998-2000 (October 1, 1998-September 31, 2000). Previous efforts which contribute significant insight and data to the development and calibration of the CWB model are as follows: (1) A preliminary Willamette Basin groundwater flow study conducted under the USGS Regional Aquifer-Systems Analysis program (RASA; Woodward et al., 1998); (2) a subsequent Willamette Basin groundwater flow study conducted in cooperation between the USGS and Oregon Water Resources Department (OWRD; Conlon et al., 2005); (3) a cooperative study of Willamette Basin surface water hydrology and quality by USGS and the Oregon Department of Environmental Quality (DEQ; Harrison et al., 1995); (4) a water quality assessment conducted through the USGS National Water-Quality Assessment program (NAWQA; Wentz & McKenzie, 1991); (5) A cooperative hydrogeological study of Portland Basin (northern extreme of the Willamette Basin) by the USGS, the OWRD, the City of Portland, OR, and Clark County, WA (McFarland & Morgan, 1996). Additional background information on the Willamette Basin, as well as the premise for model construction, can be gleaned from the OWRD Willamette River Basin Report (Oregon Water Resources Department, 1992).

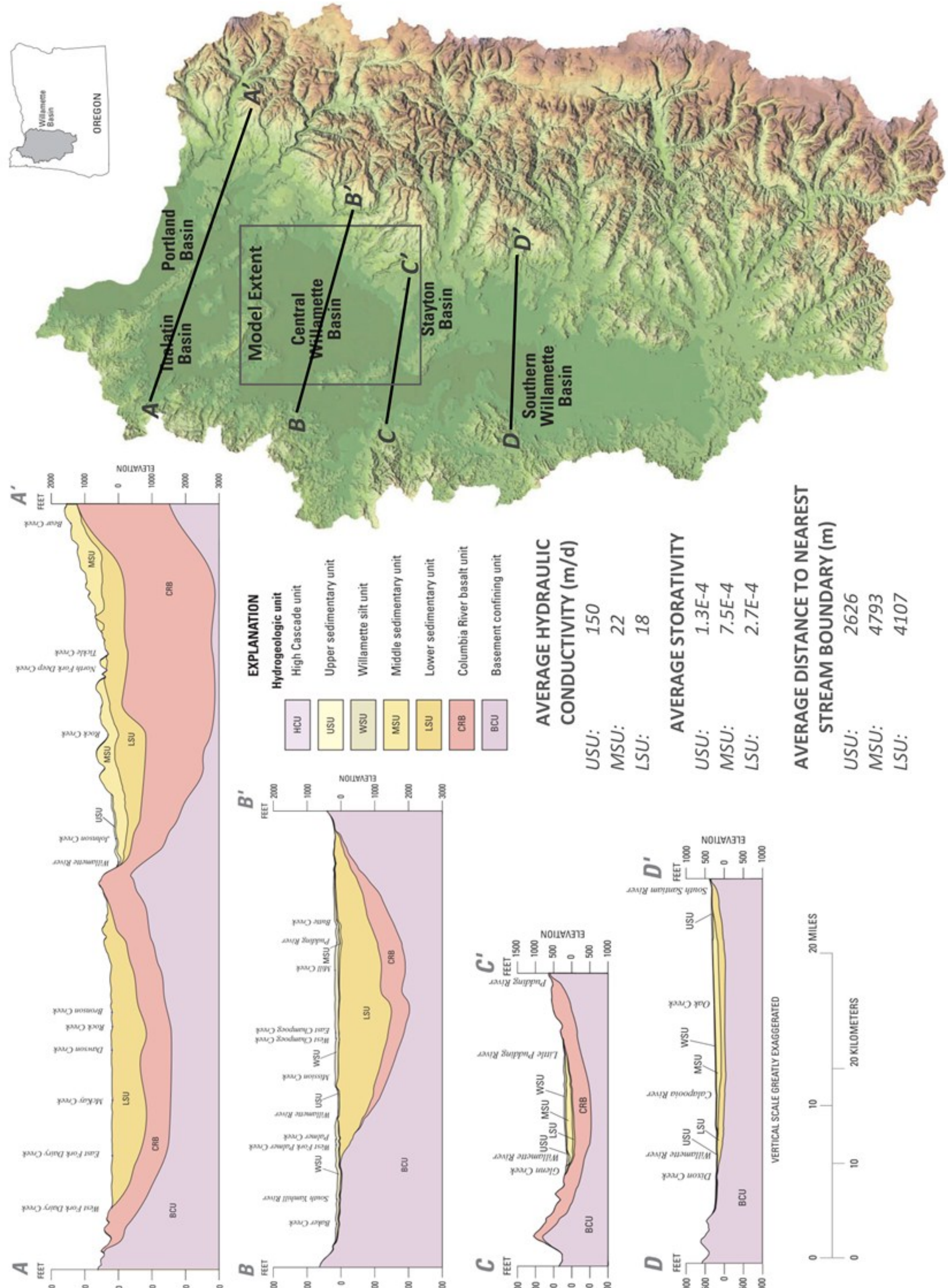

Figure 2-1. Conceptual model of the Willamette Basin lowland aquifer system. Average parameters for target SASR formations are provided. Figure adapted from Conlon et al. (2005).

Figure 2-1 depicts the areal extent of the USGS CWB model with respect to the Willamette basin. This region, while encompassing a small fraction of the basin, contains each aquifer that occurs in the lowland portion of the basin. The represented formations are as follows: (1) upper sedimentary unit (USU), (2) Willamette silt unit (WSU), (3) middle sedimentary unit (MSU), (4) lower sedimentary unit (LSU), (5) Columbia River basalt (CRB), and (6) basement confining unit (BCU).

Model employment

This study's workflow consists of 30 treatment model runs, 1 control model run, and a volumetric comparison of changes to storage and streamflow accretion between treatment and control runs. Each treatment run simulates 6 months of injection (December 1-May 31) into a single model cell, through a fully penetrating well, at a constant rate, Q_{inj}, of 0.03 m^3/s (1 ft^3/s). The 30 treatment cells are selected at random from a list of cells that represent locations where real-world production wells exist with pumping capacities greater than 0.03 m^3/s, as determined by the USGS (Conlon et al., 2005; Appendix C). The 30 treatments are equally divided into the three predominant, shallow aquifers of the Willamette Basin: the upper sedimentary unit (USU), middle sedimentary unit (MSU), and lower sedimentary unit (LSU). During treatment, the injection period is followed by 6 months where injection is removed and boundary conditions are identical to the control run (June 1-November 30). During the control run, flux is recorded from the model's surface water boundaries. This flux represents the natural flow between aquifers and surface water, and provides baseline data for system behavior with no experimental stress. Treatment fluxes are compared to the control fluxes at each time step, which provides a basin wide total for change to storage and streamflow.

Storage Efficiency

The desired time period for SASR storage is based on the temporal distribution of water availability and scarcity, which will vary by region. In the Willamette Basin, surface water is abundant for roughly 6 months of the year—the "wet-6"—and surface water is scarce for roughly 6 months of the year—the "dry-6." From a water resource management perspective, the wet-6 are months in which surface water is still available for appropriation, while the dry-6 are months in which additional surface water rights are no longer available (Oregon Water Resources Department, 2012). Additional surface water storage is of greatest utility during the dry-6, and therefore

$$E_{storage} = \frac{Volume\ of\ injected\ water\ held\ in\ storage\ during\ the\ dry{-}6}{Volume\ of\ water\ injected\ during\ the\ wet{-}6} \times 100 \qquad (5)$$

Since Q_{inj} is 0.03 m^3/s for each simulation, modeled storage efficiency is referred to in terms of unit storage efficiency. Unit storage efficiency (%) can be calculated for a constant injection rate as

$$E_{storage,unit} = \frac{Q_{inj} \times t_{inj}}{V_{storage}} \times 100 \qquad (6)$$

where t_{inj} is the time during which injection occurs and $V_{storage}$ is the modeled volume of storage that is maintained throughout the dry-6. Since this volume of storage decreases with time, unit storage volume (m^3) is calculated as the average storage throughout each time step during the dry-6

$$V_{storage} = \frac{\sum_i^n V_{storage}^i}{n} \qquad (7)$$

where n is the number of time steps (each model time step is 3.1 days) during the dry-6.

Available Storage and Rates

Storage efficiency does not address volumetric storage potential or feasible injection rates. These additional factors are quantified using widely applicable methods and basic hydrogeologic parameters. The end result is a useful, order-of-magnitude estimate of how and how much storage could be utilized in a storage-efficient aquifer.

A primary consideration is whether or not there is head space in the aquifer in which to store additional water. To estimate volumetric storage potential, V_{max}, this analysis uses the approximation made by Woody (2009) that

$$V_{max} = \bar{S} \times A \times \overline{max\Delta h} \tag{8}$$

where $\bar{S}$ is the average aquifer storage coefficient of the aquifer over the areal aquifer extent, A, where storage efficiency is deemed acceptable. $\overline{max\Delta h}$ is the average maximum acceptable rise in the aquifer head surface for a given area, calculated from steady state model conditions as depth to water minus 6.1 m (20 ft) as a safety factor. It is therefore assumed that injection will not cause head in the target aquifer to elevate within 6.1 m of land surface at the basin scale, which is the assumption of a similar methodology employed by Woody (2009). Note that the $\overline{max\Delta h}$ is calculated in this study after subtracting the safety factor from each individual value of $max\Delta h$.

While V_{max} is useful in describing how much storage exists, the rate at which a single SASR well can inject water will determine how many wells would be required to utilize this storage. Maximum injection rate, $Q_{inj,max}$, is calculated for each model cell as

$$Q_{inj,max} = SC_{inj} \times max\Delta h \tag{9}$$

where SC_{inj} is the specific capacity of injection, which is equal to

$$SC_{inj} = \frac{Q_{inj}}{s_{inj}} \tag{10}$$

where s_{inj} is the temporary increase in head surface elevation during injection at a certain rate. The general tradeoff between specific capacity and depth to water is as follows for a given injection rate: A low specific capacity location requires a large

$max\Delta h$, while a high specific capacity location requires a smaller $max\Delta h$. Maximum injection rates are achieved at large specific capacity locations with large depth to water. To calculate SC_{inj} throughout the model domain, we use the following equation based on the Cooper-Jacob (1946) solution for drawdown in a well:

$$\frac{Q_{inj}}{s_{inj}} = \frac{\bar{T}}{0.183 log\left(\frac{2.25\bar{T}t_{inj}}{{r_w}^2\bar{S}}\right)} \tag{11}$$

where r_w is the radius of a well, which is assumed to equal 0.15 m in this analysis. This relatively large radius is characteristic of high capacity wells.

Storage Efficiency Metric

It is clear from previous research that storage efficiency increases with SDF in simplified aquifer-stream systems (Bredehoeft & Kendy, 2008). SDF in such systems is the emergent relationship between transmissivity (*T*), storage coefficient (*S*), proximity to stream boundaries (*a*), and duration of stress to the system (*t*). SDF is calculated using CWB model parameterization and a geographical information system (GIS).

Distance is likely the simplest of the three variables to conceptualize, particularly in ideal, 2-dimensional aquifer models. Yet complications can be expected to arise as system complexity increases. While there are undoubtedly more sophisticated mapping techniques to measure proximity, “distance to closest in-layer surface water boundary” is used as a simplification of such techniques. In-layer surface water boundaries are boundaries that have direct hydraulic connection to the aquifer of interest. Measurement of *a* as the closest in-layer stream does not account for complex and irregular geometries, but loosely accounts for anisotropy—disproportionate vertical and horizontal permeability—caused by horizontal sedimentary bedding planes.

The CWB model is the source of *S* and *T* parameters for this study. *Reasonable* values for these parameters are based on field studies and well logs, and serve to bracket the wide range of plausible values for similarly behaving volumes of aquifer space (i.e. layers and zones). The parameters throughout space are calibrated to *likely* values when constrained by spatially explicit, known boundary conditions, as well as observations over time of groundwater head and surface water stage. It is an important caveat that the CWB model is one interpretation of the actual values of *S* and *T* throughout space, and that SDF therefore has an inherent and difficult to quantify uncertainty. In addition, *S* and *T* values are most likely to be accurate as an average for similarly behaving units, and thus should not be interpreted as estimates for any specific location.

CHAPTER 3
RESULTS

Correlation to SDF

SDF exhibits strong correlation to storage efficiency (r^2=0.9253) at sampled locations in the CWB (Figure 3-1). The correlation is similar for sampled locations in each aquifer layer. As a result, storage efficiency can be approximated for a given value of *SDF* for all locations and layers—as

$$E_{storage} = 7.7 \ln\left(\frac{SDF}{t_{inj}}\right) + 92 \qquad (12)$$

where *SDF* is in units of days and calculated by (1), and t_{inj} is equal to 180 days. When using (12) throughout the CWB, it is possible to obtain efficiency values slightly over 100%. For *SDF* over 500 days, storage efficiency is assumed to be 100%.

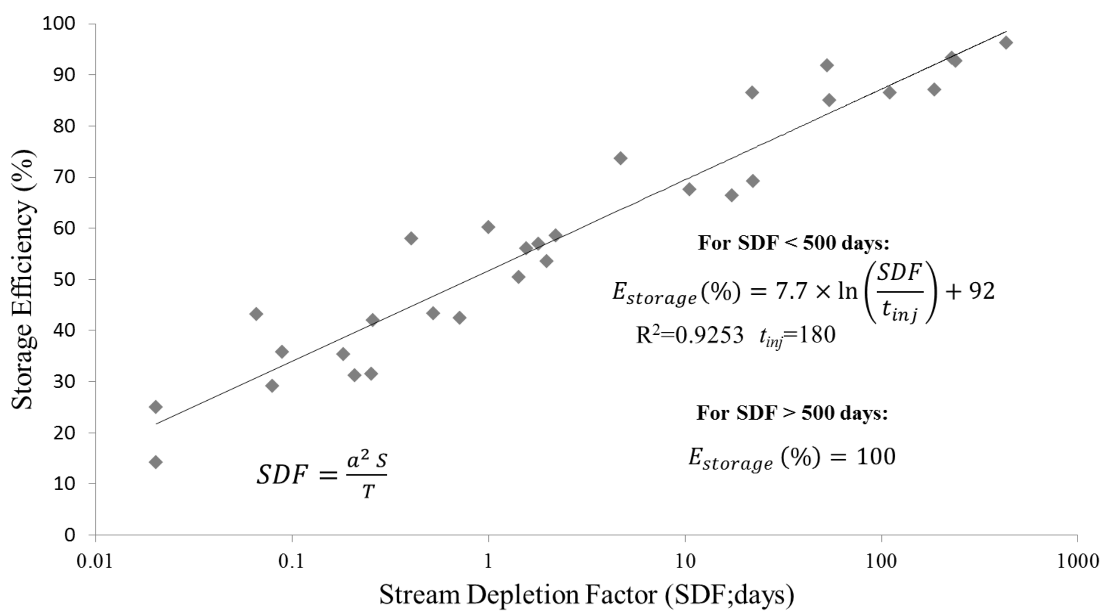

Figure 3-1: SDF versus storage efficiency. Stream depletion factor (SDF)—a function of transmissivity (*T*), storage coefficient (*S*), and distance from a well to the nearest in-layer stream boundary (*a*)—exhibits strong correlation to modeled SASR storage efficiency at sampled locations in the CWB.

Storage Efficiency

S, *T,* and *a* were used to calculate *SDF* throughout the 3 shallow aquifers in the CWB model (USU, MSU, LSU), and (12) was then used to approximate storage efficiency based on calculated *SDF*. Figure 3-2 shows the probability distribution of storage efficiency. Storage efficiency varies dramatically between the 3 shallow aquifers of the CWB. It is clear that the MSU has a high proportion of storage efficient locations. A large proportion of the LSU locations are moderately storage efficient while a large proportion of the USU locations are storage inefficient. These results suggest that the MSU is the only of the 3 aquifers with potential for highly efficient SASR storage.

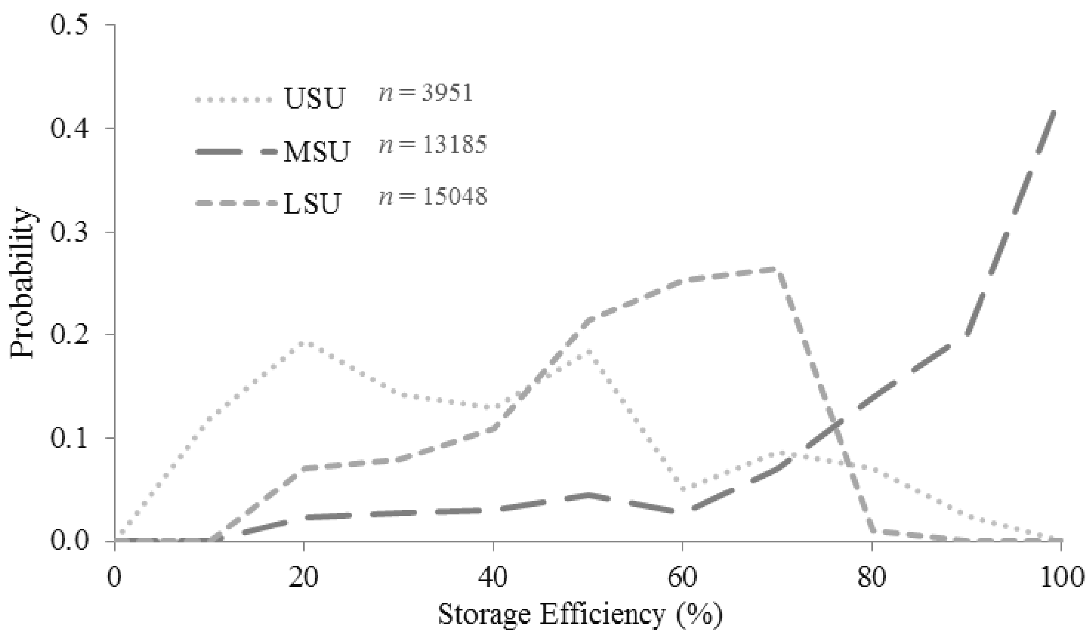

Figure 3-2. Probability distribution of storage efficiency. The lines represent the probability that a randomly selected model grid cell (305 m by 305 m) in the Central Willamette Basin (CWB) would be capable of the associated storage efficiency. Storage efficiency was calculated using (12). The three represented layers are the lower sedimentary unit (LSU), middle sedimentary unit (MSU), and upper sedimentary unit (USU).

The storage efficiency map (Figure 3-3) shows storage efficiency throughout the MSU in the CWB. Storage efficiency is visualized in 6 classes, where red indicates least efficient and green indicates most efficient. Also shown are stream boundaries for the entire model, active in-layer stream boundaries used to determine a in SDF calculations, and sample locations where treatment model runs were performed. White cross hatch is used in Figure 3-3 to identify locations where $Q_{inj,max}$ is greater than $\bar{Q}_{inj,max} = 810$ m^3/day. The significance of these locations is addressed in the following section.

Figure 3-3 illuminates several important phenomena with respect to storage efficiency. It is apparent that high storage efficiency locations exist over a large and contiguous geographical area. The aquifer parameters and sufficient multidirectional distancing from in-layer stream boundaries combine to form a large, central region of high storage efficiency. This efficient region is made possible by an overlying, less permeable unit—the WSU—which serves as an aquitard between the MSU and overlying surface water bodies. The region amounts to 22% of the total land cover in the CWB— 385 km^2 of 1750 km^2. Bands of moderately efficient locations run parallel to in-layer stream boundaries. The least efficient locations are associated with a combination of higher transmissivity alluvial material, as well as close proximity to in-layer boundaries. With the exception of higher transmissivity alluvial material, the linear distance between high and low efficiency locations is relatively short—less than 10 km in most cases. Where high transmissivity material adjoins lower transmissivity material, this distance is truncated.

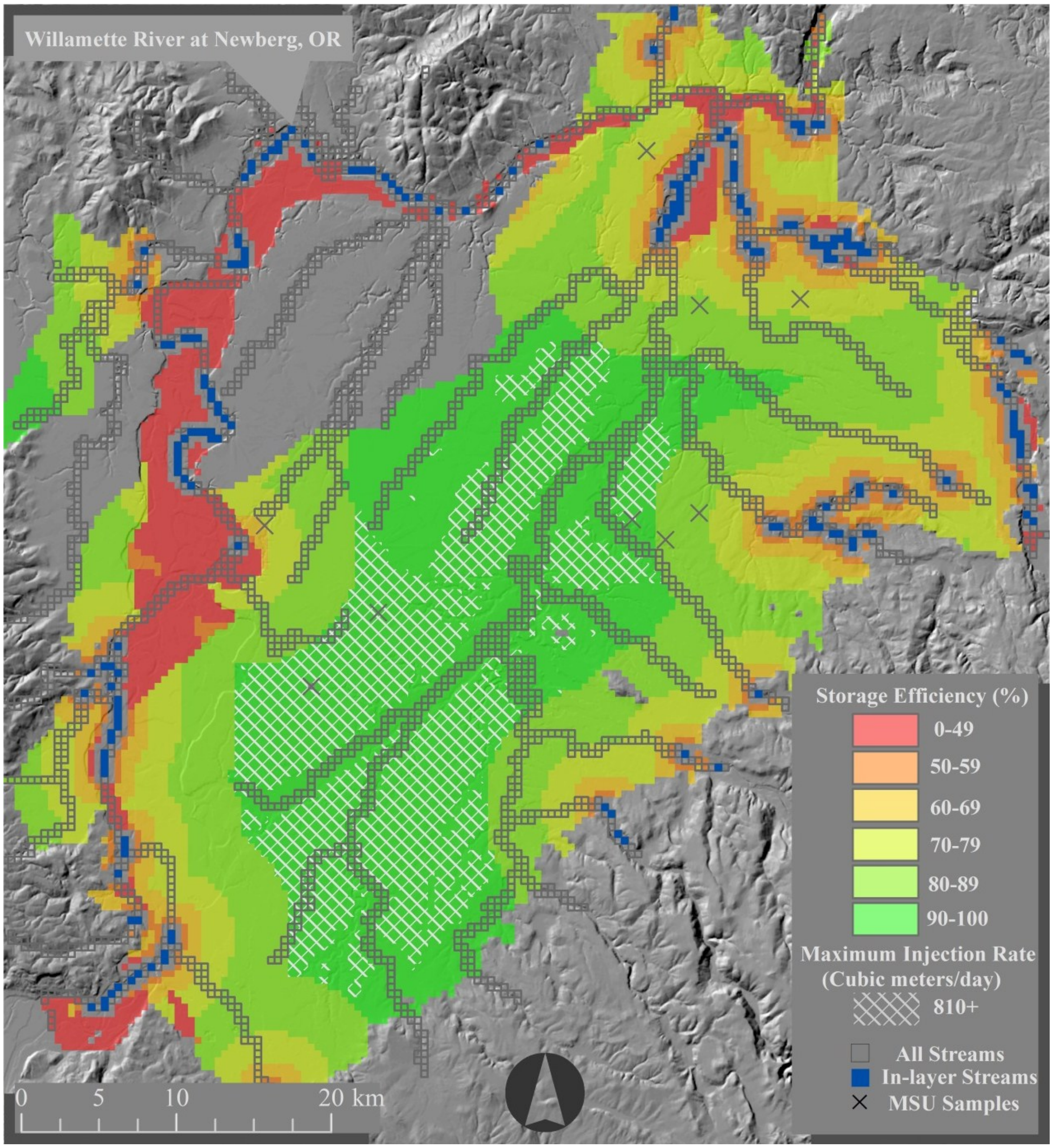

Figure 3-3. Storage efficiency map of the MSU in the CWB. White cross hatch indicates maximum injection rates are greater than the areal average of 810 m^3/day, as determined by local transmissivity and average depth to water. Cross hatch indicates accessible, efficient storage using SASR.

Available Storage and Rates

Estimates of available storage and practical injection rates focus on the central region of the MSU where storage efficiency is 90% or greater. Within this region A=385 million m^3, $\overline{max\Delta h}$=5.47 m, $\bar{T}$=260 m^2/day, and $\bar{S}$=0.00119. Using (8), V_{max} is estimated at 2.51 million m^3. $\bar{Q}_{inj,max}$ is estimated at 810 m^3/day. Assuming t_{inj}=180 days, 17 wells—roughly 35 m deep and 0.3 m in diameter—would be required to inject and store V_{max}. Note that the above calculations are made using areal averages and that higher injection rates could be enabled by preferentially siting wells in locations with higher $Q_{inj,max}$. Since these locations correspond to greater $\overline{max\Delta h}$, and represent a smaller areal extent, preferential siting would also increase the density of available storage.

The white cross hatch over the highly efficient extent in Figure 3-3 indicates locations where $Q_{inj,max}$ is greater than $\bar{Q}_{inj,max}$. If wells are preferentially cited in locations with above average $Q_{inj,max}$, $\bar{Q}_{inj,max}$ increases to roughly 1680 m^3/day. With the targeted A decreasing to 164 million m^2, $\overline{max\Delta h}$ increasing to 9.02 m, and S increasing to 0.00162, V_{max} decreases only slightly to 2.40 million m^3. The significance of preferential siting is that the number of required wells is reduced to 8 with minimal reduction in potential storage. This study therefore reports V_{max} and $\bar{Q}_{inj,max}$ based on preferential siting.

CHAPTER 4
DISCUSSION

Results indicate that a layer present throughout the lowland extent of the Willamette Basin—the MSU—is capable of storing water at high storage efficiency. This is at least the case in the CWB. Hydrogeologic conditions of the MSU are known to change from the northern to southern reaches of the basin as the overlying, less permeable WSU thins. It is therefore expected that storage efficiency in the MSU will be less in the southern half of the Willamette Basin than in the CWB. These results are nevertheless a positive indication that SASR could provide additional storage within the CWB and in similar basins around the world.

The volumetric potential for efficient storage found in the CWB—2.40 million m^3—is minute in comparison to the potential storage of regional surface water reservoirs. Reservoirs in the Willamette Basin, for example, hold maximum usable storage of anywhere from 39 million m^3 at Cottage Grove Dam and Lake to 396 million m^3 at Detroit Dam and Lake (U.S. Army Corps of Engineers, 2002). The total amount of surface water storage potential within the 13 major reservoirs in the basin is greater than 1.9 billion m^3. Demands for this water are high, however, and it is unlikely that additional reservoirs will be constructed in the Northwestern United States. Cost per *additional* unit storage is therefore useful in comparing the relative utility of SASR. Cost-effectiveness of ASR storage has been a primary reason for its widespread and rapid growth, and this relationship is well documented by Pyne (2005). It is likely that SASR would be similar in terms of cost-effectiveness.

With the estimated 8 large, shallow wells required to store 2.40 million m^3, the requisite infrastructure required to access SASR storage in the CWB is likely to be modest. Though implementation is beyond the scope of this study, one can envision cost effective strategies to access this storage.

Volumetric storage potential is also likely to be greater in more arid basins than in the CWB. It is notable that a temperate basin with high ambient water tables has displayed even moderate storage potential. Increased feasibility of SASR is likely in semi-arid and arid regions. This would be enabled by increased depth to water. In addition to the increased volumetric storage and injection rates, greater depth to water also suggests a lower degree of connectivity between groundwater and surface water resources. Reduced stream density common to more arid regions might combine with decreased groundwater-surface water connectivity to increase the effective distance between SASR wells and surface water boundaries. The net result when compared to CWB conditions may be increased volumetric storage potential at higher rates. Providing transmissivity and storage coefficients are the same as in the MSU, high storage efficiency would exist over greater areal extent.

When considering SASR management in other basins, water resource managers should seek aquifer conditions that permit injection while restricting the propagation of changes in head to nearby surface water boundaries. While high injection rates are enabled in part by high transmissivity, delayed propagation of head—characteristic of low diffusivity formations— is enabled in part by low transmissivity. This represents an inherent tradeoff in the ideal magnitude of transmissivity when assessing aquifers in any basin.

To assess potential options given this tradeoff, it is useful to assume the case in which we wish to locate a well in a high transmissivity aquifer. The goal is to inject and store large volumes of water. To enable this condition—in which injected water is largely stored—we can alter several parameters independent of transmissivity. One option is to limit the diffusivity of the target aquifer by selecting an area with high storage coefficient. Another option is to increase the distance over which head perturbations must travel from the well to a surface water boundary. The final option–which is ultimately constrained by the nature of a seasonal aquifer storage strategy—is to limit the duration of an injection-pumping cycle. Regional modeling can help determine how storage coefficient and transmissivity vary across landscapes at the basin scale and a GIS can be used to determine distances to key surface water boundaries. These two processes can together inform at the basin scale where SASR is targeted, and SDF can be used as a unifying metric.

This study has demonstrated a strong correlation between SDF and storage efficiency (12), which is to be expected based on the findings of Jenkins (1968). This specific relationship will change, however, in different groundwater systems. It is a realistic and practical goal for future research to universalize the relationship between SDF and storage efficiency in an analytical solution. Without a more universal metric for storage efficiency, modeling exercises similar to this study will be required to determine its regionally applicable relationship to SDF.

Jenkins and Talyor (1974) remind us that the SDF is “a value of time that reflects the integrated effects of the following: irregular, impermeable boundaries; stream meanders; aquifer properties and their areal variations; distance to the [location] from the stream; and imperfect hydraulic connection between the stream and the aquifer.” It follows that SDF can be modified to be accurate in any aquifer system, so long as these effects are addressed. Two key observations can be made from this statement with respect to storage efficiency. The first is that basic measures of S,T, and a (as is used in this study) are likely to be sufficient predictors of storage efficiency in a simplistic, relatively homogeneous system. The second is that more complex systems will necessitate a more sophisticated approach—and likely more variables—for determining the effective SDF of any location. Lessons can be learned from Miller et al. (2007), for example, through their concise review of aquifer boundaries effects and the resultant accuracy of SDF. A robust, universal storage efficiency metric would maintain accuracy through a wide range of system complexity.

Even with a more universal metric, much of how a parameter-to-storage efficiency link would manifest itself would be determined by the mechanisms used to reduce uncertainty and risk. A prudent option would be to establish zones—certain formations of specified areal extent—at the regional scale that minimize these two factors. We could establish these zones as “SASR Management Areas.” SASR development would be constrained to well-studied management areas and individual operations would base decisions on site-specific hydrogeologic assessment.

Establishment of management areas would require a much more extensive understanding of the subtleties of storage efficiency than can be gleaned from this study. Future studies may wish to quantify the capacity to minimize uncertainty and risk associated with regional management of SASR.

Uncertainty could be limited through selection of management areas based on aquifer properties and characteristics. Since the MODFLOW framework is intended to model Darcy flow (flow through porous media) as opposed to non-Darcy flow (i.e., pipe flow through fractured rock), the uncertainty is likely to be lowest in porous media and highest in fractured rock. The assumptions internal to SDF reflect Darcy flow as well. Since this study seeks storage in basin fill sediments with characteristic Darcy flow tendencies, this effort to reduce uncertainty is already incorporated in these results. There are additional qualities—homogeneity, large aquifer width, and absence of major faults for example—that are not addressed in this study but could be incorporated to further reduce uncertainty. Uncertainty could also be reduced with increased capacity to model heterogeneity and non-Darcy flow at a basin scale, along with increased resolution of groundwater field methods and modeling.

Given uncertainty, risk will result from unanticipated interference with surface water rights. This would occur if actual efficiency of an SASR operation were less than the estimated efficiency. In this case, the recovery stage of SASR would result in significant depletion of surface water flow. The consequence is that a management strategy intended to store water would in fact result in additional burden on surface water resources. Risk of interference could be minimized by delineating management areas based on conservative estimates of SDF, calculated with low-end values of storage coefficient and distance, and high-end values of transmissivity. Limiting management areas to regions that exhibit high SDF over a significant geographic extent, as opposed to small pockets, could also minimize such risk.

CHAPTER 5
CONCLUSION

As with any ASR strategy, effectively siting a SASR operation should be a balance between the ability to inject water into an aquifer and the ability of the aquifer to constrain outflow of the injected water, once in storage. The limitations to injection imposed by transmissivity, storage coefficient, and ambient depth to water are well documented and are observed in this study. The inclusion of storage efficiency in optimizing shallow aquifer storage has gone largely without consideration. While historical drawdown can be used to infer high storage efficiency in confined, geologically isolated aquifers, shallow aquifers require a more rigorous approach. Storage potential in shallow aquifers could therefore be enabled by robust methodologies that quantify storage efficiency.

This study suggests that the high-SDF locations required for SASR do exist in the CWB. It also supports the possibility that high-SDF conditions can simultaneously allow for significant injection rates given substantial depth to water constraints. High storage efficiency locations can be identified with some certainty using SDF, which entails a basin scale understanding of aquifer parameters and layer-specific surface water boundaries, as well as basic measure of proximity to surface water boundaries. Overall, this study indicates potential for prudent application of SASR as a seasonal, freshwater storage mode. The study also underscores the inherent variability in storage efficiency between and within differing shallow aquifers. Widespread utilization of shallow aquifer storage potential will necessitate extensive shallow aquifer characterization.

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APPENDICIES

Appendix A: Storage efficiency versus recovery efficiency

Given established nomenclature for ASR efficiency, it is important to define how efficiency is interpreted in this study. Efficiency of ASR can be defined in two ways based on perspective: the water resource management perspective and the operations perspective. The efficiency of ASR is conventionally cited from the operations perspective. This perspective, which is held by ASR operations concerned with maintaining the quality of injected water, can be described in terms of

$$E_{recovery} = \frac{Volume\ of\ injected\ water\ recovered}{Volume\ of\ injected\ water} \times 100 \tag{1}$$

which equals 100% in an ideal scenario, can be as low as 25%, and averages 80-85% (Pyne, 2005). This form of efficiency is conventionally referred to as *recovery* efficiency. Since injected water is subject to mixing with ambient groundwater via dispersion and migration down gradient via advection, recovery efficiency is a useful way to quantify potential changes to water quality during the time while injected water is maintained in storage.

From a water resource management perspective, efficiency can be described in terms of

$$E_{storage} = \frac{Volume\ of\ stored\ water}{Volume\ of\ injected\ water} \times 100 \tag{2}$$

where the volume of water stored is considered over some finite length of time. We introduce and refer to this metric as *storage* efficiency. This term relates to the volumetric flux between groundwater and surface water caused by pumping or injection. The fraction of injected water that is not stored is assumed to migrate from the well site, and to ultimately be lost to surface water. Hydrogeologically speaking, it follows that the same fraction of subsequently pumped water will be captured from surface water. Water quality notwithstanding, storage efficiency is useful in quantifying the actual capacity to temporally offset surface water availability using any form of aquifer storage.

Appendix B: Willamette Basin case study

Growth of ASR in Oregon has been catalyzed by highly suitable aquifers and progressive regulation that facilitates the ASR process (Oregon Administrative Rules, 690-350-0010-0030). It follows that ASR has become a key component of the statewide Integrated Water Resources Strategy (OWRD et al., 2012). Yet limitations will be reached as Oregon ASR continues to grow. Some of these limitations fall into the category of sociopolitics, some economics, and some hydrogeology.

The Willamette Basin is one of the most well studied basins in Oregon, and is a prime example of the limitations imposed by distribution of storage using ASR. In the Willamette Basin, high population densities combine with summertime pressures on water supply to make ASR a viable solution for water storage needs. Of 7 high volume ASR operations in the basin, 6 successfully store water in fractured basalt aquifers. The 5 largest operations store water in the Columbia River basalt (CRB; Woody, 2009). The most apparent drawback of ASR in the basalt is poor distribution of storage. CRB aquifers of substantial thickness are only present in the northern half of the Willamette Basin (Figure 2-1), where many municipalities between Portland and Salem reside. The basalt aquifers constitute a prime resource of limited extent. Interest in ASR in the southern Willamette Basin (SWB)—including the cities of Eugene and Corvallis—has spawned several low volume storage operations that use exempt wells to store water in confined, fractured, volcanic aquifers of low permeability (Embleton, 2012). Despite potential for low volume storage operations, lack of access to more permeable, confined aquifers will likely limit SWB ASR to similarly scaled operations.

Storage in shallow aquifers using SASR could increase both volumetric storage potential and its distribution in Oregon. To do so, state water resource managers will need to reconcile the differences between management of ASR and SASR.

The State of Oregon has focused statewide ASR planning efforts on the volumetric capacity to inject water into aquifers. The culmination of this work is a statewide assessment of potential ASR sites (Woody, 2008) which builds on the ASR assessment methodology of Brown (2005). Woody additionally uses a hydrogeologic suitability metric that relates hydrogeologic injection capacity to the available water supply rates for production wells throughout the state. The Woody metric uses depth to water, transmissivity, and conservative extrema of storativity and well radius, to analytically estimate maximum potential injection rates for wells. Oregon uses the results from the Woody metric to describe potential annual ASR storage potential in river basins throughout the state. Knowledge of the distribution of potential storage can also help concentrate state efforts to increase implementation of ASR.

The Woody metric relies on the assumption that injected water is equivalent to stored water, which is often valid in confined aquifers. Yet one can imagine a shallow aquifer scenario in which a well in close proximity to a stream allows for high rates of injection, but where the injected water quickly discharges to the stream. In this case, water is clearly not stored for a useful time period. Statewide ASR planning that targets shallow aquifers must incorporate an additional hydrogeologic metric that describes the efficiency at which injected water is stored for a useful time period—a storage efficiency metric.

Appendix C: CWB production wells

Sample #	Layer	Row	Col	Q (m^3/d)	County	Code
1	USU	117	30	6948	MARI	5303
	USU	32	106	6067	CLAC	53487
	USU	114	28	4257	MARI	4946
	USU	75	27	4184	YAMH	6453
	USU	110	37	4135	MARI	4854
2	USU	74	27	4037	YAMH	6452
3	USU	137	34	3866	MARI	16803
	USU	138	25	3817	POLK	1667
4	USU	109	42	3523	MARI	4858
5	USU	141	30	3278	POLK	1695
	USU	73	28	3254	YAMH	6363
6	USU	125	28	3034	MARI	5354
	USU	38	112	2936	CLAC	12949
	USU	99	39	2936	WUP2	29
7	USU	66	33	2936	YAMH	5489
	USU	94	41	2789	MARI	2959
8	USU	96	38	2789	MARI	2943
	USU	120	33	2789	MARI	4974
	USU	100	32	2740	MARI	2931
9	USU	88	35	2667	YAMH	6715
	USU	65	33	2642	YAMH	5499
10	USU	39	60	2618	MARI	1052
	USU	158	24	2618	WUP2	21

Sample #	Layer	Row	Col	Q (m^3/d)	County	Code
	LSU	71	14	14900	YAMH	6395
1	LSU	62	56	7853	MARI	1331
	LSU	62	57	7853	MARI	1320
	LSU	59	58	7584	MARI	18828
2	LSU	76	43	7095	MARI	2902
3	LSU	78	22	6655	YAMH	6409
	LSU	62	63	5236	MARI	1399
	LSU	61	63	5113	MARI	1314
4	LSU	74	86	4208	MARI	1636
	LSU	123	38	4208	MARI	17870
5	LSU	76	47	4110	MARI	2341
	LSU	46	66	3939	MARI	17816
	LSU	75	78	3939	MARI	1611
	LSU	49	61	3792	MARI	1182
	LSU	63	56	3621	MARI	1318
	LSU	64	62	3596	MARI	1381
	LSU	57	52	3548	MARI	1243
	LSU	52	80	3376	MARI	606
6	LSU	129	33	3376	MARI	5384
	LSU	55	61	3303	MARI	1262
7	LSU	71	15	3278	YAMH	6397
	LSU	65	63	2960	MARI	1382
	LSU	82	24	2960	YAMH	6507
8	LSU	57	26	2936	YAMH	5404
	LSU	76	22	2887	YAMH	6421
9	LSU	53	52	2765	MARI	1240
	LSU	68	43	2765	MARI	1449
	LSU	66	27	2691	YAMH	5484
10	LSU	68	62	2642	MARI	1386
	LSU	46	60	2618	MARI	1138
	LSU	55	50	2569	MARI	1242

Sample #	Layer	Row	Col	Q (m^3/d)	County	Code
	MSU	75	102	16832	MARI	1736
	MSU	50	116	11377	CLAC	13297
	MSU	62	112	9566	CLAC	12662
	MSU	102	95	7756	MARI	54371
1	MSU	53	111	7120	CLAC	13344
	MSU	61	123	5603	CLAC	52275
	MSU	66	82	4991	MARI	893
	MSU	89	24	4918	YAMH	6572
2	MSU	110	53	4771	MARI	50927
	MSU	63	87	4282	MARI	839
	MSU	34	95	4257	MARI	172
	MSU	77	53	4110	MARI	2349
3	MSU	85	101	4037	MARI	1962
4	MSU	88	106	3988	CLAC	2186
	MSU	77	139	3768	CLAC	53757
5	MSU	86	46	3694	MARI	2537
	MSU	91	91	3694	MARI	2054
	MSU	89	91	3670	MARI	1920
	MSU	46	118	3621	CLAC	50991
	MSU	54	130	3596	CLAC	12456
	MSU	58	128	3523	CLAC	12548
	MSU	45	85	3474	MARI	358
6	MSU	84	111	3425	CLAC	2569
	MSU	130	77	3425	WUP2	25
	MSU	131	62	3401	MARI	18385
7	MSU	125	56	3327	MARI	4497
	MSU	74	90	3303	MARI	1708
	MSU	81	104	3229	CLAC	2083
	MSU	97	60	3156	MARI	2820
8	MSU	99	63	3156	MARI	2821
	MSU	79	95	3034	MARI	1758
9	MSU	30	103	2985	CLAC	8578
	MSU	61	119	2960	CLAC	12582
	MSU	74	63	2960	MARI	2362
	MSU	78	101	2960	CLAC	2050
	MSU	116	81	2960	MARI	17229
	MSU	69	150	2936	CLAC	51358
	MSU	75	71	2887	MARI	2424
10	MSU	52	126	2814	CLAC	12292
	MSU	85	109	2765	CLAC	2576
	MSU	77	134	2716	CLAC	2060
	MSU	76	51	2667	MARI	2348
	MSU	107	64	2667	MARI	3906
	MSU	80	55	2593	MARI	2490
	MSU	119	56	2593	MARI	4325
	MSU	112	65	2569	MARI	4050
	MSU	112	77	2520	MARI	3219
	MSU	126	74	2496	MARI	4441
	MSU	57	109	2471	CLAC	13358
	MSU	102	72	2471	MARI	3706

	No. Wells	Avg. Q	Total Q
USU	23	3516	80859
MSU	50	4082	204093
LSU	31	4464	138378

Appendix D: Data for sampled locations

Layer	Sample	Aquifer Thickness (m)	*MaxΔh* (m)*	*T* (m^2/day)	*S*	*a* (m)	$E_{storage}$ ***	*SDF* (d)
USU	1	18.3	-5	3344	1.8E-04	1829	35%	0.2
USU	2	3.0	10	57	3.0E-05	6466	41%	22.3
USU	3	16.8	-4	3066	1.7E-04	610	25%	0.0
USU	4	18.6	-15	3400	1.9E-04	4278	60%	1.0
USU	5	17.4	-7	3177	1.7E-04	610	14%	0.0
USU	6	16.5	-9	3010	1.6E-04	2155	32%	0.3
USU	7	6.1	-9	1115	6.1E-05	5332	23%	1.6
USU	8	7.0	-15	1282	7.0E-05	1099	43%	0.1
USU	9	4.0	-19	725	4.0E-05	1952	31%	0.2
USU	10	18.0	-12	337	1.8E-04	1928	45%	2.0
	Average	12.6	-8.4	1951	1.3E-04	2626	35%	2.8
MSU	1	3.0	0	67	3.0E-04	3448	85%	54.3
MSU	2	12.5	9	274	1.2E-03	7226	93%	238.3
MSU	3	5.5	3	120	5.5E-04	6408	87%	187.4
MSU	4	3.0	-5	67	3.0E-04	4915	86%	110.2
MSU	5	5.2	5	114	5.2E-04	1524	68%	10.6
MSU	6	4.9	-2	107	4.9E-04	3408	92%	53.0
MSU	7	24.7	5	541	2.5E-03	9758	96%	434.6
MSU	8	7.0	8	154	7.0E-04	7089	93%	229.4
MSU	9	3.0	7	67	3.0E-04	1952	66%	17.4
MSU	10	6.1	-2	134	6.1E-04	2198	87%	22.0
	Average	7.5	2.8	164	7.5E-04	4793	85%	135.7
LSU	1	424.6	10	7950	4.2E-04	5182	50%	1.4
LSU	2	337.1	13	6312	3.4E-04	1293	36%	0.1
LSU	3	136.9	7	2562	1.4E-04	3658	42%	0.7
LSU	4	383.4	6	7179	3.8E-04	9390	74%	4.7
LSU	5	362.1	13	6780	3.6E-04	2198	42%	0.3
LSU	6	54.3	-8	1016	5.4E-05	2760	58%	0.4
LSU	7	28.0	10	525	2.8E-05	5799	57%	1.8
LSU	8	190.2	19	3561	1.9E-04	1219	29%	0.1
LSU	9	281.3	11	5268	2.8E-04	3138	43%	0.5
LSU	10	460.6	13	8623	4.6E-04	6430	59%	2.2
	Average	265.8	9	4978	2.7E-04	4107	49%	1.2

*Calculated as the depth to water minus a 6.1 m (20 ft) safety factor
**Max injection rate assumes a maximum well screen of 200 m if aquifer thickness exceeds this value; a fully screened aquifer is assumed otherwise
***Unit Storage efficiency results independent of max injection rate calculations

Appendix E: Linearity of storage efficiency

The calculated unit storage efficiency is the product of a uniform, constant injection rate. In a linear aquifer-stream system, the unit storage efficiency will remain constant regardless of injection rate. If this were the case in a real-world context, the unit storage efficiency could be used to inform SASR management regardless of desired injection rates. If a system does not behave in a linear fashion, SASR management must account for this. A test of system linearity will therefore be useful in guiding how water resources managers interpret the unit storage efficiency metric. Step-testing is an accepted field method for measuring system linearity (Kelly and Anderson, 1980) and is applied it to this study. We measure the linearity of the aquifer-stream system through multiple simulations of injection at sampled locations with high unit storage efficiency—ultimately 8 locations in the MSU. 7 simulations simulate a range of injection rates from 0.0001 m^3/s to 100 m^3/s, with order of magnitude differences between them. Storage efficiency for each simulation is calculated using a procedure identical to that used to calculate unit storage efficiency.

In Figure E-1, we see that below a certain threshold the efficiency increases dramatically with increases in injection rate, and that above this threshold the efficiency slowly declines with further increases in injection rate. We attribute the trend at low injection rates to a relative decrease in the influence of numerical error caused by rounding—not to a physical process. We attribute the decreasing trend that occurs across realistic injection rates to the process-based nonlinearity in the aquifer. A high and low value of water use are provided for comparison: the average annual water use of 1 million m^3/year for 2000 homes (assuming 1.325 m^3/home/day) and the 1995 total water withdrawal of 1100 million m^3 for the entire Willamette Basin (U.S. Geological Survey, 2001). Since injection rate is shown on a logarithmic scale, it is apparent that storage efficiency is influenced to a very small degree by injection rate.

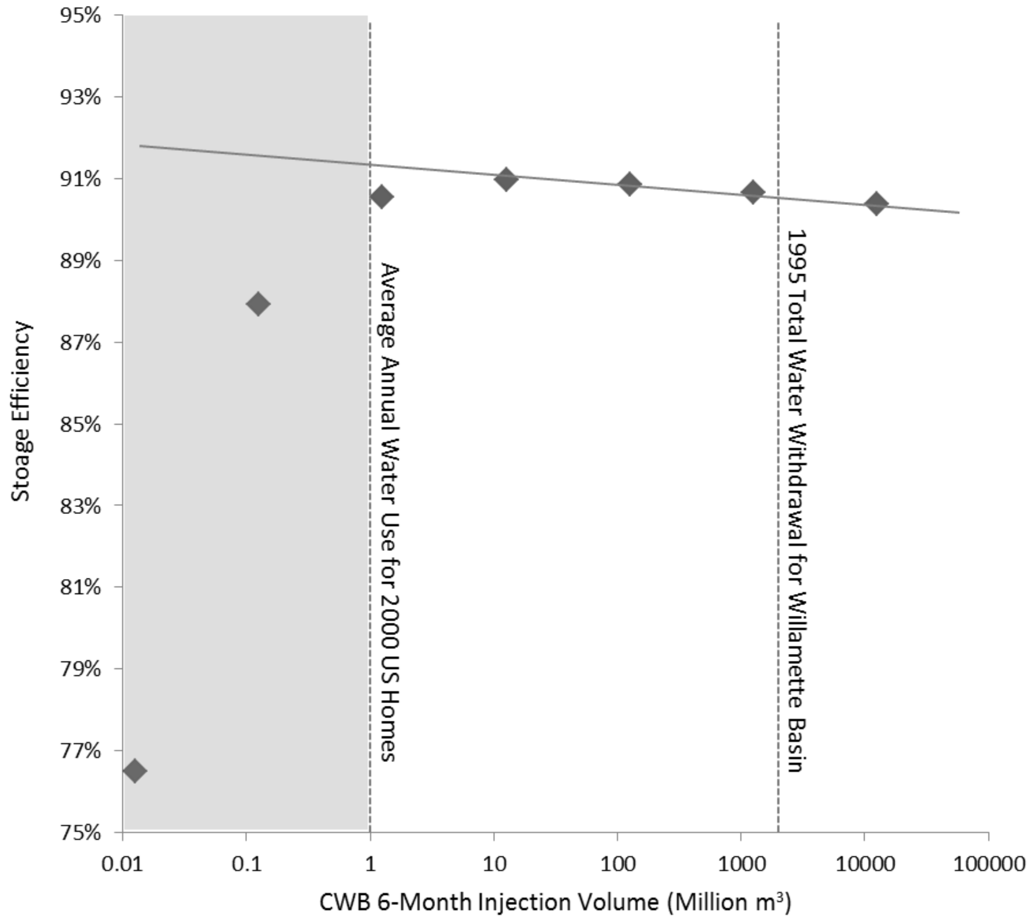

Figure E-1. Storage efficiency sensitivity to wet-6 injection volume. Water injected into 8 locations in the middle sedimentary unit (MSU) during the wet-6 months. Each of 8 locations has a unit storage efficiency of 80% or greater.

Appendix F: Correlation to capture fraction metrics

Leake et al. (2011) propose a modeled capture fraction—or "time-to-threshold"—approach to categorize streamflow depletion tendencies of myriad pumping locations. They categorize locations by the pumping duration required for streamflow depletion to equal a certain fraction of the instantaneous pumping rate. The opposite is calculated for each location in this study: the *injection* duration required for streamflow *accretion* to reach 10% of the instantaneous injection rate. Figure F-1 illustrates strong logarithmic proportionality between storage efficiency and a capture fraction metric such as this one.

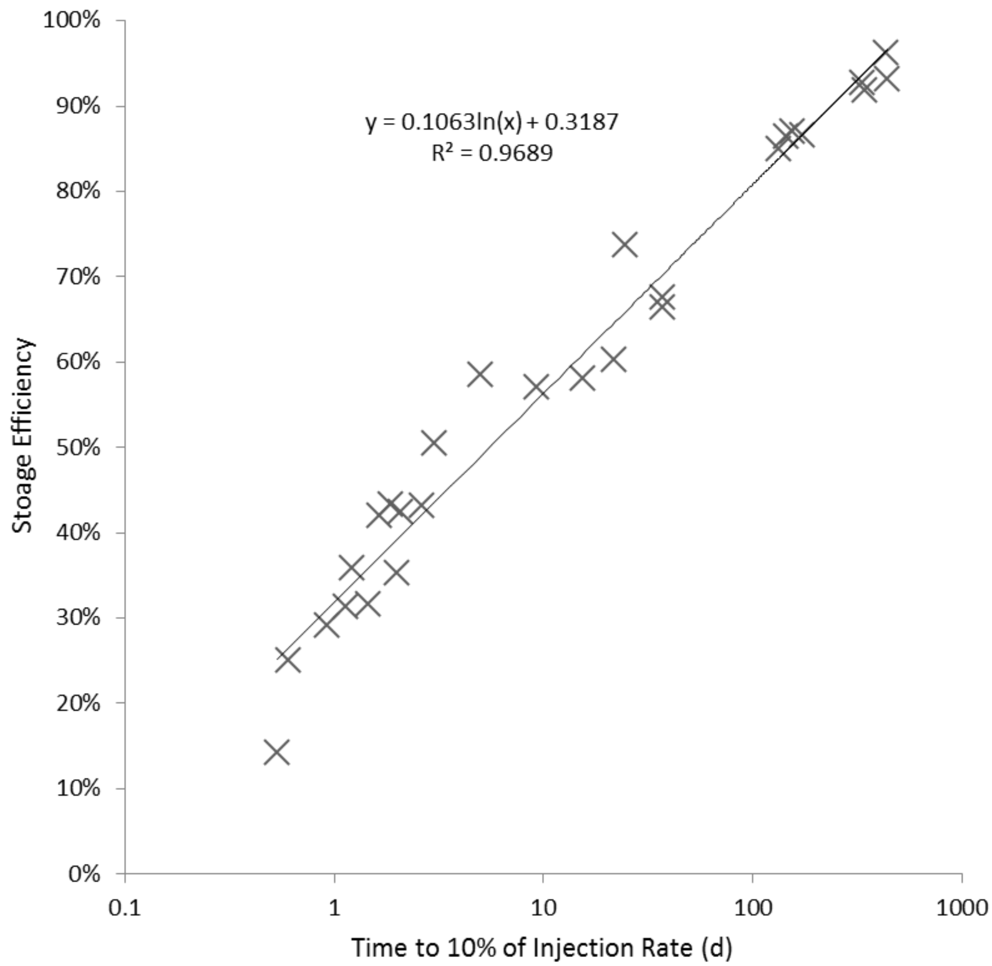

Figure F-1. Storage Efficiency correlation to a capture fraction metric.